Science of the Total Environment 914 (2024) 169862

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Tackling climate change through wastewater reuse in agriculture: A prioritization methodology

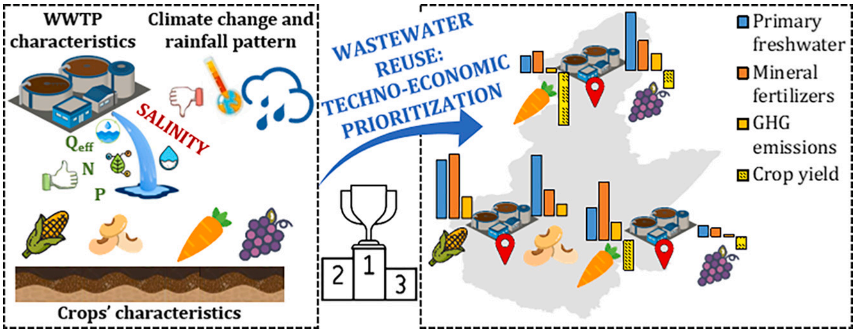
Luca Penserini [a], Alessandro Moretti [b], Matia Mainardis [b], Beatrice Cantoni [a], Manuela Antonelli [a,*]

[a] Politecnico Milano, Department of Civil and Environmental Engineering (DICA) - Environmental Section, Piazza Leonardo da Vinci 32, 20133 Milano, Italy
[b] Università degli studi di Udine, Polytechnic Department of Engineering and Architecture (DPIA), Via del Cotonificio 108, 33100 Udine, Italy

HIGHLIGHTS

- A novel prioritization approach is proposed to assess reclaimed wastewater reuse.
- Effluent quality, crop nutrient requirements and rainfall are jointly evaluated.
- Reuse suitability depends on the match with crops surrounding the treatment plant.
- Primary water and mineral fertilizers are the main contributors to economic savings.
- Crop yield losses due to salinization are crucial for reusing reclaimed wastewater.

GRAPHICAL ABSTRACT



ARTICLE INFO

Guest Editor: Maite Pijuan

Keywords:
Fertigation
Salinization
Nutrients recovery
Greenhouse emissions
Direct wastewater reuse
Techno-economic assessment

ABSTRACT

Water shortages, exacerbated by climate change, are posing a major global challenge, particularly impacting the agricultural sector. A growing interest is raised towards reclaimed wastewater (RWW) as an alternative irrigation source, capable of exploiting also the nutrient content through the fertigation practice. However, a prioritization methodology for selecting the most appropriate wastewater treatment plants (WWTPs) for implementing direct RWW reuse is currently missing. Such prioritization would benefit water utilities, often managing several WWTPs, and policymakers in optimizing economic asset allocation. In this work, a prioritization framework is proposed to evaluate WWTPs' suitability for implementing direct RWW reuse considering both WWTP and surrounding territory characteristics. This procedure consists of four key steps. Firstly, a techno-economic model was developed, in which monthly mass balances on water and nutrients are solved by matching crop requirements, rainfall conditions, and effluent characteristics. Economic suitability was quantified considering economic benefits due to savings in freshwater resource, mineral fertilizers and avoided greenhouse gases emissions, but also losses in crop yield due to RWW salinity content. Secondly, a classification procedure was coded to select representative WWTPs among a set of WWTPs, based on their size, presence of nutrient removal processes, and type of crops in their surroundings. The techno-economic model was then applied to these selected WWTPs. Thirdly, input parameters' relevance in determining WWTP suitability for RWW reuse was ranked. Finally, scenario analyses were conducted to study the influence of rainfall patterns and nutrient treatment

---

* Corresponding author.
E-mail address: manuela.antonelli@polimi.it (M. Antonelli).

https://doi.org/10.1016/j.scitotenv.2023.169862
Received 13 October 2023; Received in revised form 20 December 2023; Accepted 31 December 2023
Available online 5 January 2024

removal on the RWW reuse feasibility. The type of crops surrounding the WWTPs and RWW salinity content resulted to be crucial elements in determining WWTPs suitability for RWW reuse implementation. The proposed methodology proved to be an effective support tool for policymakers and water utilities to assess the techno-economic feasibility of direct RWW reuse, generalizing results to several combinations of WWTPs and crops.

Abbreviations

CA	carrots
DRY	scenario of dry rainfall pattern year
EC	electrical conductivity
EU	European Union
F/V	fruits and vegetable crops
GHG	Greenhouse gases
L-WWTP	large WWTP
M-WWTP	medium WWTP
MA	maize
MEAN	scenario of mean rainfall pattern year
N	nitrogen
N-WWTP	WWTP with N removal process
NO-WWTP	WWTP without nutrient removal process
NP-WWTP	WWTP with N and P removal processes
P	phosphorus
RWW	reclaimed wastewater
S-WWTP	small WWTP
SEED	seed crop
SO	soybean
VI	vines
WET	scenario of wet rainfall pattern year
WWTP	wastewater treatment plant

1. Introduction

The effects of climate change are becoming progressively more visible worldwide. Southern and Western EU countries are particularly affected by persistent droughts, worsened by recurrent heat waves during the year's hottest months (Toreti et al., 2022). Moreover, we are experiencing a continuous rising of temperatures (Quinteiro et al., 2019). The combined water and heat stress severely affects agriculture, which is known to be the most water-intensive sector, with estimates of about 70 % of global freshwater withdrawals for crop irrigation (Mainardis et al., 2022; Rossi et al., 2021). Significant reduction in crop yield may be encountered in these conditions (Breshears et al., 2021; Slafer and Savin, 2018), with relevant economic damages to farmers. As the overall freshwater demand rises, potentially boosting conflicts among involved stakeholders, finding alternative water sources for agriculture becomes crucial (Ricart and Rico, 2019).

To lower the stress on the over-exploited conventional freshwater sources, direct reuse of reclaimed wastewater (RWW) from wastewater treatment plants (WWTPs) may provide controlled water for crop irrigation, promoting a circular economy approach (Khan et al., 2022; Delli Compagni et al., 2020). Besides water reclamation, it is also possible to recover most of the nutrients still contained in the treated effluents through the fertigation practice. In fact, nutrients in WWTPs effluents, specifically nitrogen, phosphorus and potassium, are normally present in a soluble form, which eases their uptake by crops when compared to conventional mineral fertilizers (Mainardis et al., 2022). The utilization efficacy of mineral fertilizers by crops is limited, and this leads to their overload and subsequent dispersion in the environment, enhancing the eutrophication potential. Essentially, RWW reuse can lower mineral fertilizers excess, as well as the indirect greenhouse gases (GHG) emissions associated to their production (Moreira da Silva et al., 2022). With rising costs of mineral fertilizers, due to their uneven geographical distribution and the current uncertain economic situation (Baffes and Koh, 2022), adopting fertigation practices offers to farmers a potential reduction in overall expenses. However, WWTPs effluents normally show a higher organic matter content than freshwater, as well as a higher salinity, which may alter the equilibrium in soil structure and its microbial communities, negatively affecting nutrient uptake (Ofori et al., 2021). A negative impact of increased soil salinity may be observed on crop yield, depending on peculiar crop and soil characteristics (Gao et al., 2021).

The recent adoption of the new EU legislation on direct agricultural reuse of RWW (EU Commission, 2020), which specifies the required physical-chemical and microbiological thresholds (differentiated into four quality classes), is expected to standardize the previously heterogeneous legislative framework, encouraging the implementation of direct RWW reuse. However, a potential constraint, limiting the adoption of this virtuous practice, is associated to the lack of a prioritization methodology to select the most appropriate WWTPs on which to implement agricultural reuse. In fact, water utilities normally manage hundreds of WWTPs of extremely different sizes and characteristics (e.g., absence or presence of specific treatment processes), making hard to decide for which WWTP would be more convenient to implement the RWW reuse.

Vivaldi et al. (2022) proposed a set of quantitative indices that combine physical and operational features of both WWTPs and irrigation districts equipped for RWW use, quantifying their environmental benefits. However, this procedure requires input data which can be derived only after the RWW reuse has been implemented. Then, it serves as an evaluative procedure, rather than a prioritization methodology. Conversely, Bolinches et al. (2022) proposed a cost-benefit analysis for prioritizing RWW reuse implementation considering all project-related costs and benefits, but overlooking potential adverse impacts, such as the potential soil and crop salinization due to RWW salinity content.

In this perspective, the aim of this work is to develop a robust prioritization framework for researchers, practitioners, and water utilities, that could be used as a support tool for selecting the most appropriate WWTPs for the full-scale application of direct agricultural RWW reuse, where economic asset should be allocated. Such framework considers effluent characteristics, local geographical conditions, including climate and rainfall patterns, and the locally cultivated crops, with their specific water and nutrient requirements and sensitivity to salinity. The proposed methodology includes four steps. Firstly, a techno-economic model was developed. This model solves monthly mass balances on water and nutrients to achieve two key objectives resulting from the implementation of RWW reuse: (i) quantifying the amount of water and nutrients required by crops that can be fulfilled by WWTPs, and (ii) determining the economic savings associated with water, nutrients, and avoided GHG emissions and the economic loss in terms of crop yield due to the higher salinity content of RWW. Secondly, a procedure aimed at the classification of a set of WWTPs was defined, based on their specific characteristics (size, treatment train, crops located nearby the WWTP), for the identification of the most representative WWTPs. The developed techno-economic model was applied only to this smaller group of WWTPs, being indicative for a higher number of WWTPs with similar characteristics (i.e., WWTPs in the same class). This permitted to draw general findings on WWTPs suitability for the implementation of direct RWW reuse, that can be extended to the whole class of WWTPs to which the representative ones belong. Thirdly, the relevance of model input parameters was assessed through a correlation analysis, resulting in a ranking of their respective importance in determining the economic feasibility of the direct RWW reuse resulting from the model. Finally, as fourth step, a scenario analysis was performed setting two scenarios to understand how a variable rainfall pattern or a reduced nutrient removal in WWTPs can affect the economic convenience of implementing direct RWW reuse. The proposed framework has been applied referring to two high-GDP (gross domestic product) areas in northern Italy (the provinces of Brescia and Udine), comprising 95 WWTPs, and it can be easily replicated and extended to alternative locations with the specification of local WWTPs, crops and climate characteristics.

2. Materials and methods

The prioritization framework, elaborated to assess and compare WWTPs suitability for the implementation of direct RWW reuse in agriculture, is here presented.

2.1. Techno-economic model description

The techno-economic model proposed by Mainardis et al. (2022) was upgraded by: integrating (i) water and nutrients monthly mass balances, (ii) estimating GHG emissions, (iii) assessing the salinity impact on crop yield, and (iv) calculating economic savings and losses for each of the previous outputs.

Firstly, irrigation water volumes to be delivered for satisfying crop requirements were estimated based on monthly water balances during the growing season. The net monthly irrigation requirement I_i (m^3 ha^{-1} $month^{-1}$), which can be totally or partially provided by RWW, was estimated as:

$$I_i = \frac{ET_i - R}{E} \tag{1}$$

where i is the considered crop, ET_i (m^3 ha^{-1} $month^{-1}$) is the crop i evapotranspiration, considered equal to its water requirement, and R (m^3 ha^{-1} $month^{-1}$) is the effective rainfall, calculated through Turc's equation (Trajkovic and Kolakovic, 2009) from monthly accumulated precipitation data over the considered areas. The difference between ET_i and R represents the actual net water amount uptaken by the crop, and must be divided by the overall irrigation efficiency E, computed as:

$$E = E_s \cdot E_d \cdot E_a \tag{2}$$

The three terms in Eq. (2) depend on the local agricultural soil pedology and represent the irrigation system efficiency (E_s), the water distribution efficiency from source to fields (E_d), and the application efficiency (E_a).

Regarding nutrients, only nitrogen and phosphorus were investigated, being the only ones considered by the current EU reuse regulation. Once I_i was estimated, the loads of the nutrients $MASS_{i,j}$, (kg_j ha^{-1} $month^{-1}$) contained in the RWW were obtained as:

$$MASS_{i,j} = I_i \, C_{j,WWTP} \, E_{fert,j} \tag{3}$$

where j stands for nitrogen (N) or phosphorus (P), $C_{j,\ WWTP}$ is the concentration of nutrient j in the WWTP effluent and $E_{fert,\ j}$ is the nutrient j uptake efficiency.

Since the amount of water and nutrients contained in RWW are related and cannot vary independently, but crops have their specific requirements, the actual quantities of water and nutrients delivered to the crops through fertigation were obtained by identifying the limiting factor. Thus, calculated I_i and $MASS_{i,j}$ were iteratively compared with the monthly crop's water and nutrient requirements (kg_j ha^{-1} $month^{-1}$): when fertigation-supplied nutrients do not meet crop requirements, water is the limiting factor. In this case, the saved volume of primary freshwater W_i (m^3 ha^{-1} $month^{-1}$) corresponds to the whole volume of RWW exiting the WWTP and delivered to crops, and the saved amount of nutrients $F_{i,j}$ (kg_j ha^{-1} $month^{-1}$) corresponds to the load of nutrients present in the RWW, while mineral fertilizers should be added to fulfill the nutrient gap. Instead, when either N or P are in excess, the delivered RWW volume (W_i) must be reduced to avoid overfertilization, integrating water and the other nutrient gaps with alternative sources. For the months in which either crops' water or nutrient requirements are equal to zero, no RWW should be supplied to the crops.

The actual quantities of water and nutrients delivered to the crops from the WWTPs were considered equal to the saved volume of primary freshwater W_i (m^3 ha^{-1} $month^{-1}$) and the saved amount of nutrients $F_{i,j}$ (kg_j ha^{-1} $month^{-1}$).

Being W_i expressed per unit of surface, it was possible to calculate the potential irrigable area (ha) through direct RWW reuse if the WWTP effluent would be entirely applied, as the ratio between the WWTP monthly flowrate and W_i.

The reduction of nutrients to be supplied by mineral fertilizers (corresponding to $F_{i,j}$) was converted into avoided GHG emissions $GHG_{AV,\ i,j}$ (kg $CO_{2,EQ}$ ha^{-1} $month^{-1}$) by assuming the replacement of traditional fertilization practices with fertigation. In particular, the direct application to soil of mineral fertilizers (ammonium nitrate and triple super phosphate) was considered for N and P supply, respectively, with their associated uptake efficiencies $E_{soil,j}$, reported in Table S1, and production emission factors EF_j, as adopted in Mainardis et al. (2022), as:

$$MF_{i,j} = \frac{F_{i,j}}{E_{soil,j} \, MF_{content,j}} \tag{4}$$

$$GHG_{AV,i,j} = MF_{i,j} \, EF_j \tag{5}$$

where, $MF_{i,j}$ is the saved amount of mineral fertilizers and $MF_{content,\ j}$ is the nutrient contained in the solid mineral fertilizer expressed as weight ratio.

For the salinity impact on crops' yield, the RWW salinity concentration, expressed as electrical conductivity (EC) (μs cm^{-1}), was compared with crop-specific salinity thresholds. Specifically, when irrigation water's EC level was higher than the crop's salinity threshold, a percentage reduction in the crop yield was assumed based on data collected from FAO (1994). The annual percentage reduction in crop yield $Y_{RED,i}$ was converted into annual mass of harvest reduction H_i (kg_i ha^{-1} yr^{-1}), considering the average annual crop production per hectare $PROD_{AVG,i}$ (kg_i ha^{-1} yr^{-1}), collected from the Fertilgest website, as:

$$H_i = Y_{RED,i} \, PROD_{AVG,i} \tag{6}$$

Based on these assumptions and inputs, the estimated model outputs are: (i) the saved volume of primary freshwater W_i, (ii) the saved amount of mineral fertilizers $MF_{i,j}$, (iii) the avoided GHG emissions $GHG_{AV,\ i,j}$ due to the reduction of applied mineral fertilizers, and (iv) the reduction of crop harvest H_i due to the increase in salinity given by the RWW.

Starting from these outputs, a simplified economic evaluation was integrated into the model to quantify overall savings and losses of the fertigation practice compared to traditional fertilization and irrigation. The reduction in primary freshwater and mineral fertilizers supply and related avoided GHG emissions were considered as economic benefits from the direct RWW reuse implementation. The economic loss due to RWW salinity impact on crop yield was considered as a drawback of direct RWW reuse. Primary freshwater and mineral fertilizers economic savings were quantified by multiplying W_i and $MF_{i,j}$ by the average costs of irrigation water (€ m^{-3}) and mineral fertilizers (€ kg_i^{-1}), respectively, assuming that no RWW fees are paid by the farmers. Costs of water, ammonium nitrate and triple superphosphate assumed for the traditional irrigation practices were retrieved from databases of local agricultural associations, as in Mainardis et al. (2022), and are summarized in Table S1. H_i were multiplied to the related average crop market prices (€ kg_i^{-1}), collected from FAO website, to obtain the annual economic loss due to the salinity-related crop yield reduction. The cost of RWW transport and distribution from WWTP to the fields was not considered, being beyond the purpose of this work. $GHG_{i,j}$ was converted in an economic benefit by considering an EU carbon permit price of 95 € $tCO_{2,EQ}^{-1}$ ("EU Carbon Permits website"). Finally, the economic outputs were summed up together to determine the surface-specific net annual saving (€ ha^{-1} yr^{-1}) due to the implementation of RWW reuse in the selected WWTPs.

2.2. Study area and data collection

In this study, 95 municipal WWTPs in two high-GDP areas in northern Italy (provinces of Brescia and Udine) were considered, having a served population equivalent higher than 2000 inhabitants, and being close to crop fields (within 0.5 km). For each WWTP, information about size and treatment train were collected, together with monitored data regarding daily effluent flowrate, N and P concentrations, and EC values.

Local precipitation data from the rainfall stations located nearby the analyzed WWTPs (ARPA FVG website; ARPA Lombardia website) were collected to calculate the average monthly effective rainfall R (Eq. (1)) in the latest 5-year period (2017–2021), and they were used as explained in Section 2.5.

The considered locations are agricultural areas where a wide variety of crops is cultivated. However, only maize (MA), soybean (SO), carrot (CA) and vines (VI) were studied, due to their local dominance. The considered months for the irrigation season were April to September, according to the selected crop's typical growth cycle. Crop-specific monthly water (Buzzacchi et al., 2008) and nutrient (Fertilgest website) requirements are reported in Table S2. Crops' salinity thresholds are detailed in Table S3, while annual average production per hectare and average market prices are summarized in Table S4.

2.3. WWTPs classification

To identify representative WWTPs, the classification of the 95 WWTPs was performed based on three parameters:

i) WWTPs size, defining three classes: small (S, PE = 2000–10,000 inhabitants), medium (M, PE = 10,000–70,000 inhabitants), and large (L, PE > 70,000 inhabitants) WWTPs;
ii) the presence of nutrient removal processes in the WWTPs, defining three classes: absence of nutrient removal (NO), only N removal (N), and combined N and P removal (NP);
iii) main crops cultivated nearby the WWTP, defining two classes: seed crops (SEED), including maize and soybean, and fruits and vegetable crops (F/V), including carrot and vines, due to their difference in terms of water requirements.

Among the 18 possible combinations, only 10 classes were identified, whose ID code was named as "SIZE-NUTRIENT REMOVAL-CROP". In fact, there are no available M-WWTPs or L-WWTPs in the studied areas with NO or N treatment train, since all the WWTPs adopt advanced nutrient removal strategies (nitrification/denitrification and chemical or biological phosphorus removal). Thus, the distinction among different nutrient removal processes was made only for S-WWTPs. In Table 1 the total number of WWTPs available for each class is reported together with the classes' summary (median and range) of the related WWTPs effluent flowrate, N and P concentrations, and EC values. For each class, a representative WWTP was selected, based on the availability of effluent quality data, preferring the WWTPs characterized by the highest number of monitored data. Only for L-WWTPs' classes, all the six available WWTPs were considered, due to the notable variations in flowrate and nutrient levels.

The developed techno-economic model was exclusively applied to this subset of 14 WWTPs, among the 95 available ones.

2.4. Input parameters ranking

The Spearman rank correlation (Schober and Schwarte, 2018) was performed to rank the relevance of the model inputs on the net annual saving associated to direct RWW reuse. Inputs related to (i) WWTPs (effluent flowrate, N and P concentrations, EC values), (ii) crops (water, N and P requirements, and salinity thresholds), and (iii) territory (effective rainfall) were considered in the regression analysis. *p*-values and T-values (standardized effects) were calculated for each input parameter through the statistical software *Minitab 21.1*, and they were used to rank the parameters' relevancy.

Table 1
Number of available and selected WWTPs and summary of classes' characteristics indicated as median and range in brackets (class ID: WWTP size - Nutrient Removal - Type of crop): WWTPs flowrate, N and P concentrations (expressed as Total Nitrogen and Total Phosphorus) and EC values.

Class ID	#available WWTPs	#selected WWTPs	Flowrate (m^3 day^{-1})	N (mg L^{-1})	P (mg L^{-1})	EC (μs cm^{-1})
S-NO-SEED	5	1	1258 (1069–1413)	18.6 (14.5–22.4)	1.5 (1.0–1.8)	796.1 (741.0–882.5)
S-N-SEED	39	1	2005 (1595–2586)	8.3 (5.6–10.6)	0.7 (0.3–1.3)	*906.3*[a] (–)
S-NP-SEED	4	1	400 (344–442)	6.3 (5.1–7.8)	1.1 (0.7–1.6)	*906.3*[a] (–)
M-NP-SEED	6	1	3648 (2765–4250)	4.2 (3.4–5.2)	0.3 (0.1–1.3)	785.4 (672.0–912.0)
L-NP-SEED	4	4	26,083 (12,377–44,601)	7.5 (5.3–11.9)	0.8 (0.3–2.8)	926.0 (906.3–1078.0)
S-NO-F/V	2	1	224 (212–249)	11.9 (10.7–12.5)	1.7 (1.5–1.9)	*906.3*[a] (–)
S-N-F/V	24	1	611 (441–1043)	11.1 (8.8–12.3)	2.5 (1.3–3.6)	1111.4 (946.0–1205.0)
S-NP-F/V	5	1	232 (137–342)	3.8 (2.8–5.0)	1.2 (0.7–1.9)	*906.3*[a] (–)
M-NP-F/V	4	1	7190 (5970–8551)	8.8 (5.4–11.8)	0.6 (0.3–0.7)	920.9 (786.0–1099.0)
L-NP-F/V	2	2	68,050 (12,304–132,618)	6.5 (5.2–8.0)	0.7 (0.6–0.9)	872.7 (671.0–1150.0)

[a] Since the EC data were not available, it was assumed equal to the average EC value among all the WWTPs (906.3 μs cm^{-1}).

2.5. Scenario analysis

Two scenarios were simulated to observe how different boundary conditions, namely rainfall pattern and a lower removal efficiency of nutrients, affect the model outputs in terms of convenience of direct RWW reuse implementation.

In the first scenario, the effects of variable rainfall patterns were analyzed. Three conditions corresponding to three benchmark years were identified based on the monthly precipitation data collected over a 5-years period from the considered rainfall stations: (i) a mean scenario (MEAN), in which monthly precipitation were assumed equal to the ones of the year with an average rainfall intensity, (ii) a rainy (WET) and (iii) an arid (DRY) scenario, where monthly precipitation of the wettest and driest years were respectively considered. The monthly precipitation data for the three considered years are reported in Table S5. In the second scenario, two different nutrient concentrations in the effluents were explored: (i) a scenario with average nutrient concentrations from real effluents and (ii) a scenario with nutrient concentrations equal to the maximum discharge limits allowed by current Italian regulation (D.M. 185/2003), assumed as constant.

3. Results and discussion

In the first two sections, the outcomes resulting from the application of the techno-economic model to the selected WWTPs obtained through the classification process are detailed. These outcomes enable to draw general conclusions on the suitability and prioritization of WWTPs for direct RWW reuse, that can be extended to WWTPs belonging to the same class. Specifically, the reductions of primary freshwater, mineral fertilizers and GHG emissions were quantified in Section 3.1, while the economic analysis results are reported in Section 3.2. In the last three sections, the influence of the input parameters variability on the economic convenience of direct RWW reuse is investigated. Section 3.3 describes the obtained ranking of the most relevant input parameters. In Sections 3.4 and 3.5, two scenarios analyses were performed to simulate how the profitability of direct RWW reuse is affected, respectively, by a variable rainfall pattern and a lower nutrient removal in WWTPs.

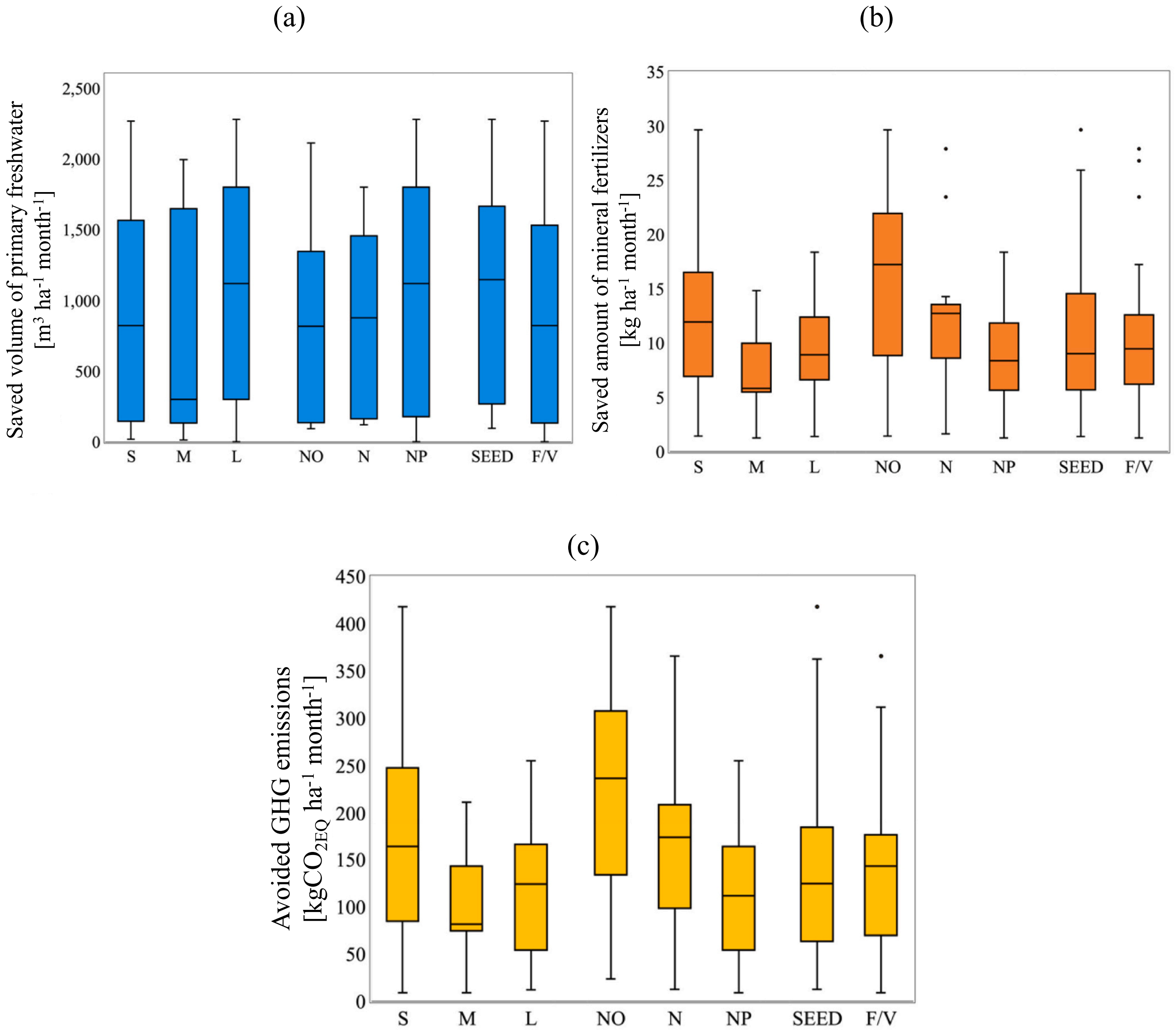


Fig. 1. Monthly surface-specific estimates of (a) saved volume of primary freshwater, (b) saved amount of mineral fertilizers and (c) avoided GHG emissions, for the identified classes.

3.1. Technical analysis

For every selected WWTP, the techno-economic model was run two times to consider both types of crops included in the crop class: maize and soybean were alternatively investigated for the seed class, while carrot and vines were alternatively investigated for the fruits and vegetables one. Three monthly outputs were estimated: (i) saved volume of primary freshwater ($W_{i,}$), (ii) saved amount of mineral fertilizers ($MF_{i,j}$) and (iii) avoided GHG emissions ($GHG_{AV,\ i,j}$). In Fig. 1, the reductions in primary freshwater, fertilizers, and GHG emissions as a function of different classes' characteristics are shown. Only the outputs obtained in the months in which RWW is actually supplied to crops are plotted, i.e., the months in which either crops' water or nutrient requirements are equal to zero (Table S2) are not considered here. In particular, for maize and vines, RWW is delivered during all the months but September (83 % of the period), for soybean RWW is delivered just in May and June (33 % of the period), while for carrots from April to June (50 % of the period).

Being the WWTP size directly proportional to the treated flowrate (and, thus, to the RWW available for reuse), the primary freshwater reduction should logically present a trend proportional to WWTPs' size. However, differently from what is expected, S-WWTPs and L-WWTPs primary freshwater reductions per hectare are not significantly different and are on average twice compared to M-WWTPs (Fig. 1a). This is due mainly to the limitation in crops nutrients' requirement, which restrains the amount of RWW deliverable to the crop. Thus, when fertigation practices are adopted, it is more advisable to account for both water and nutrient crop requirements to assess the RWW irrigation loads to be supplied to the crops, rather than exclusively considering water requirements, which is the traditional approach.

As for the presence of nutrient removal processes within WWTPs, a reduction of the median savings of both mineral fertilizers and avoided GHG emissions is observed (Fig. 1b,c) by upgrading the level of nutrient removal (from NO-WWTPs to NP-WWTPs). NO-WWTPs and NP-WWTPs showed median reductions of mineral fertilizers of 17.2 and 8.4 kg ha^{-1} $month^{-1}$, and median avoided GHG emissions of 236.7 and 111.6 kg $CO_{2,EQ}$ ha^{-1} $month^{-1}$, respectively. This confirms that a lower extent of nutrient removal in the WWTP implies a lower need for supply of mineral fertilizers to the crops and, thus, a higher saving in mineral fertilizers' costs and GHG emissions.

Finally, it emerged that monthly outputs differentiated per crop class are characterized by high variability for both seed and fruits and vegetables, even within the same class. Hence, it is difficult to identify a clear trend related to the type of crop to be irrigated, as the specific crop type significantly affects the results of the direct RWW reuse assessment.

3.2. Economic analysis

The results of the economic analysis over the whole year are summarized in Fig. 2, computed for all the types of crops. For each class, the economic contribution of each model output is reported in terms of surface-specific annual saving, which could be (i) positive, due to the savings of primary freshwater, mineral fertilizers and GHG emissions, or (ii) negative, due to crop yield loss given by RWW salinity. The potential annual saving is also reported, obtained by multiplying the overall surface-specific annual saving by the potential area which could be irrigated with the RWW from the selected WWTP. In case the economic loss is higher than the saving, RWW reuse is assumed not to be implementable, and no annual saving is thus expected.

Specific WWTP and crops' characteristics differently affect the annual saving. The presence or absence of a nutrient removal process determines how positive savings are apportioned among the three model outputs. Water and mineral fertilizers are the main contributors to the overall positive saving, with average contributions of 44.7 % and 46.9 %, respectively. However, for NO-WWTPs and N-WWTPs, the fertilizers saving contribution increases up to 63.7 %, while for NP-WWTPs the water saving contributes up to 62.3 %. Although the avoided GHG emissions are responsible for a limited economic saving, the benefit hidden behind the economic values corresponds to an avoided environmental impact, which is hard to be quantified.

Crops' class and, particularly, crops' type, are the most relevant in

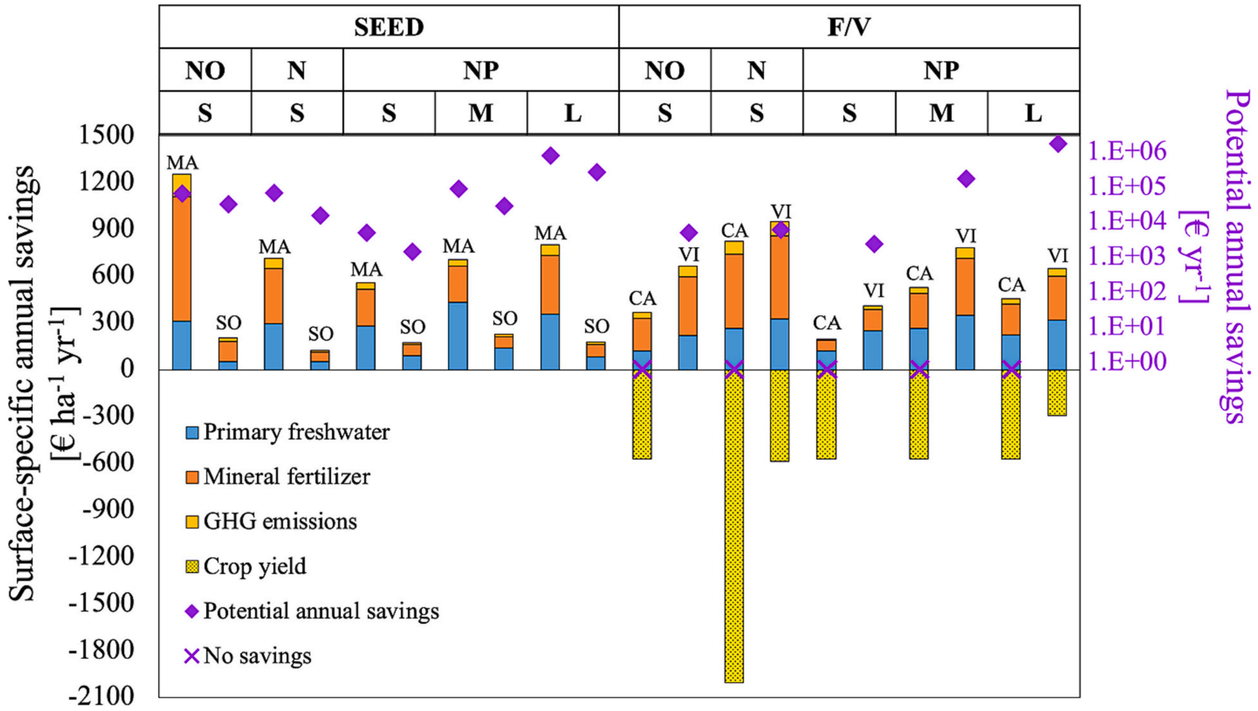


Fig. 2. Surface-specific annual savings (bars referring to the left vertical black axis) differentiated per outputs' contribution, and potential annual savings (dots referring to the $\log_{10}$-scale right vertical purple axis). Results are reported for both the type of crops (MA = maize, SO = soybean, CA = carrot, VI = vines) in each class, indicated in the top of the graph. Cases of no saving are reported with “x”.

determining the net annual saving. Seed crops show different results between maize and soybean, being the crops with the highest and lowest nutrients requirement (Table S2), respectively. Maize proved to be the most favored crop for irrigation with RWW, presenting the maximum net annual saving (1254.5 € ha^{-1} yr^{-1} for the S-NO-SEED class), while soybean presents the lowest positive saving, ranging between 124.9 and 225.9 € ha^{-1} yr^{-1}. Conversely from seed crops, which do not show a yield loss due to salinization, fruits and vegetables crops are significantly affected by effluent salinity content, being carrot and vines salinity thresholds notably lower compared to those of maize and soybean (Table S3). Even though both the considered fruits and vegetable crops show similar savings, vines determine overall net annual saving ranging from 354.3 to 782.0 € ha^{-1} yr^{-1}, while for carrots, having the highest annual crop production per hectare (Table S4), the overall net annual balance is always negative, and, thus, is considered equal to 0. Actually, there are no research studies so far in which the influence of salinity on the crop yield due to the irrigation with RWW was evaluated in economic terms. Hence, the present results highlight the importance of considering, besides the benefits, also the negative impacts of the higher salinity content unavoidably associated with RWW, since it is determinant in establishing whether direct reuse is a suitable practice (or not) for specific crops' irrigation.

Finally, WWTPs' size affects the potential annual saving, which increases with the RWW volume available from the WWTPs, and, accordingly with Fig. 1b, decreases with nutrient removal treatment. Potential annual savings are obtained assuming that the whole WWTP's flowrate can be used for crops' irrigation, thus, it represents the upper limit to which direct RWW reuse implementation could be extended maximizing the associated saving, even if this is not always achievable due to practical constraints.

From these results it emerges how the jointly application of the developed techno-economic model and the proposed classification of WWTPs allows to identify the WWTPs potentially suitable for the implementation of direct RWW reuse in terms of economic convenience. In fact, the outcomes obtained for representative WWTPs can be extended to the whole classes which they belong to, supporting water utilities, practitioners and policy-makers in the prioritization of WWTPs, optimizing economic asset allocation. Both the techno-economic model and the classification process refer to local WWTPs and territory characteristics which are readily available to collect, such as WWTPs size and treatment chain, effluent concentrations, crops characteristics and rainfall pattern, enabling the application of the proposed methodology to alternative locations. In addition, the general results here obtained can be extended to other geographical areas with similar features in terms of cultivated crops and rainfall patterns, since WWTPs specific characteristics has been observed to be the less significant in affecting the model outputs.

3.3. *Identification of the most relevant input parameters*

The dominant input parameters determining the net annual saving were identified through the Spearman rank correlation. Relative parameters' influence was ranked through the calculation of their standardized effects, which are reported in the Pareto chart in Fig. 3.

These results confirmed that the crop type is crucial for the determination of the net annual saving, as previously observed in Fig. 2. It must be remarked that crops' water and nutrient requirements affect the estimated outputs on two different levels: (i) by determining which is the limiting factor between water and nutrients to be delivered to the crop, and (ii) whether it is economically feasible or not to irrigate with RWW. In fact, crop nutrient and water requirements, together with salinity thresholds, are the most relevant parameters pointed out by the analysis, followed by the effective rainfall. On the contrary, WWTP's effluent characteristics turned out to be less relevant; in particular, effluent flowrate and phosphorus concentration, with *p*-values equal to 0.19 and 0.28, respectively, resulted as the only statistically not significant parameters. This is reasonable since neither RWW volume nor phosphorus concentration are limiting factors for direct RWW reuse, considering that (i) WWTP's flowrate is never lower than the quantity of water required for crops' irrigation, and (ii) when nutrients are the limiting factor, the limitation is always caused by nitrogen (due to the higher N:P ratio in RWW than that required by the crops).

Hence, the territory characteristics in the proximity of the WWTPs, such as crops' type and rainfall pattern, are essential to decide whether to implement direct RWW reuse, not only for the quantification of the economic benefits, but also for understanding if the implementation is feasible, as for maize, or not, as for carrots.

Moreover, it must be reminded that constant prices were considered for irrigation water, mineral fertilizers, and EU carbon permits, while these prices, especially the latter two, are significantly fluctuating on the market, thus it may be interesting in the future to study how this variability affects the net annual savings.

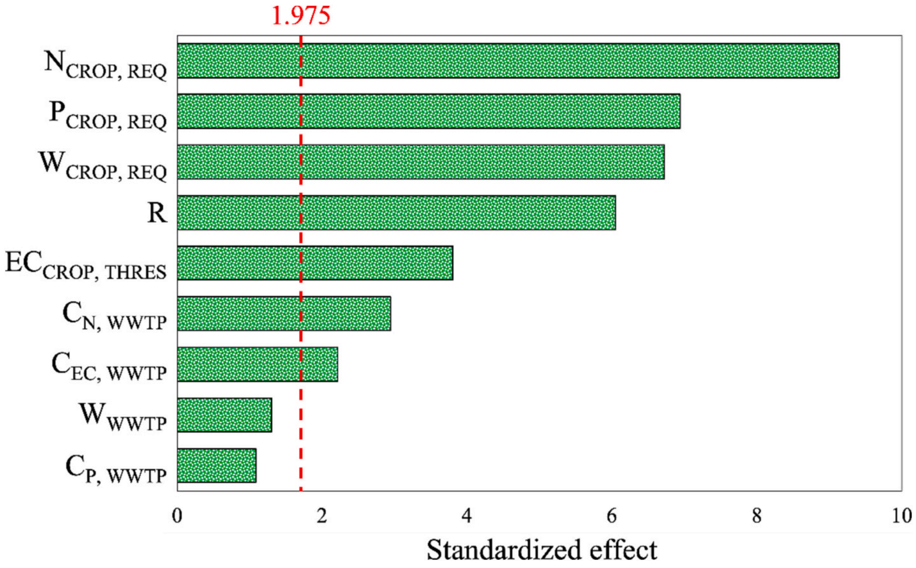


Fig. 3. Pareto chart of the parameters' standardized effects (α = 0.05) on the net annual saving. The dotted red line represents the standardized effect threshold above which the parameter is significant (*p*-value lower than α). $N/P/W_{CROP, REQ}$: N or P or water crop requirement, R: effective rainfall, $EC_{CROP, THRES}$: crop salinity thresholds, $C_{N/P/EC, WWTP}$: N or P or EC concentrations in the WWTP effluent, W_{WWTP}: effluent flowrate.

3.4. Effect of variable rainfall pattern

The effective rainfall emerged as one of those territorial characteristics which strongly influence the outcomes of the techno-economic feasibility of RWW reuse. Thus, being rainfall patterns directly affected by climate change, it is crucial to incorporate climate change scenarios within the techno-economic assessment, to provide results which reflect realistic conditions. Hence, three yearly rainfall patterns (MEAN, DRY, and WET) were investigated to quantify how climate change alters the suitability of direct RWW reuse obtained for an average year. The obtained results are reported in Table S6, while they are graphically visualized in Fig. 4 for maize and vines.

As expected, the driest the considered year, the higher is the net annual saving originating from direct RWW reuse. This is an important evidence, since climate change is expected to exacerbate the periods of droughts and water scarcity in general. In this context, direct RWW reuse implementation will become more and more crucial in facing freshwater scarcity, contributing to provide water to the agricultural sector, and, thus, mitigating potential conflicts among stakeholders competing for the primary freshwater resource. However, depending on the classes, the rainfall pattern variations affect differently the net annual saving, and it is not possible to draw general conclusions. For maize irrigation (Fig. 4a), the highest variation in the net annual saving for the MEAN scenario occurs in S-N-WWTPs (+32.4 %) and in M-NP-WWTPs (−38.8 %) for DRY and WET scenarios, respectively, while for vines irrigation (Fig. 4b), the highest increase in net annual saving occurs for L-NP-WWTPs (+31.3 %). Similar results were obtained for soybean and carrots.

Hence, the effective rainfall confirmed its relevancy in determining the benefits related to direct RWW reuse, but further research is needed to identify significant trends in the correlation between WWTPs territorial position and the considered model output. Information about the primary freshwater availability and the fee that farmers are willing to pay for RWW are not included in the model. Hypothetically, the lower is the primary freshwater availability, the higher would be the need for alternative water sources (e.g., RWW), and the higher may be the price that could be paid for RWW. In addition, the cost of RWW transport and distribution from WWTPs to crop fields could be considered as well in the model. Pistocchi et al. (2018) calculated a total average wastewater reclamation cost (additional treatment, energy, and distribution costs) of 0.25–0.50 € m^{-3} in Italy, which would be an additional cost to be covered by water utilities, while Giannoccaro et al. (2019) reported that the lack of reliable irrigation networks in Apulia region (Italy) is a significant economic issue, implying that almost 30 % of RWW could not be conveyed at the farm gate. Thus, a more detailed focus should be made on the need for subsidies from public institutions, which could be viable measures to close the economic balance and incentivize the implementation of direct RWW reuse, especially in situations of water scarcity exacerbated by a dry year, which is a circumstance more and more common due to climate change.

3.5. Effect of variable effluent nutrient concentrations

In case of direct RWW reuse for irrigation purposes, the Italian D.M. 185/2003 authorizes an increase in the effluent discharge limits for nitrogen and phosphorus up to 35 mg L^{-1} and 10 mg L^{-1}, respectively, which are significantly higher than the concentrations reported for this case study (Table 1). Thus, it may be generally perceived as recommended a lower extent of nitrogen and phosphorus removal in the WWTP, aimed at producing effluents rich in nutrients, which would be more suitable for direct crops irrigation.

Therefore, a further scenario analysis was performed to evaluate how the positive saving deriving from RWW reuse would be affected from an increase in nutrients' concentration in the effluent. Two different nutrient concentrations in the effluent were assumed: (i) nutrient concentration in real effluents, including their monthly variability, and (ii) constant nutrient concentration equal to the maximum discharge limits allowed by D.M. 185/2003. However, being the limit for phosphorus excessively high compared to the WWTPs' effluent characteristics (the maximum measured phosphorus concentration was equal to 3.6 mg L^{-1}), only the N concentration limit (35 mg L^{-1}) was considered, together with a typical N:P ratio, which is substantially constant and equal to 10. Thus, phosphorus limit concentration was assumed to be 3.5 mg L^{-1}.

Results are reported in Table S7 and summarized in Fig. 5, where only the positive outputs (i.e., savings related to primary freshwater, mineral fertilizers, GHG emissions, and the overall saving, i.e., the sum of these three outputs) are jointly presented. The output data were normalized with respect to their maximum value to be plotted on the same scale. Fig. 5 allows to easily observe which scenario implies the highest benefits: if dots undergo the bisector, it is convenient to keep the real effluent nutrient concentration, while, in the opposite case, it could be profitable to raise the effluent nutrient concentration to the discharge limits.

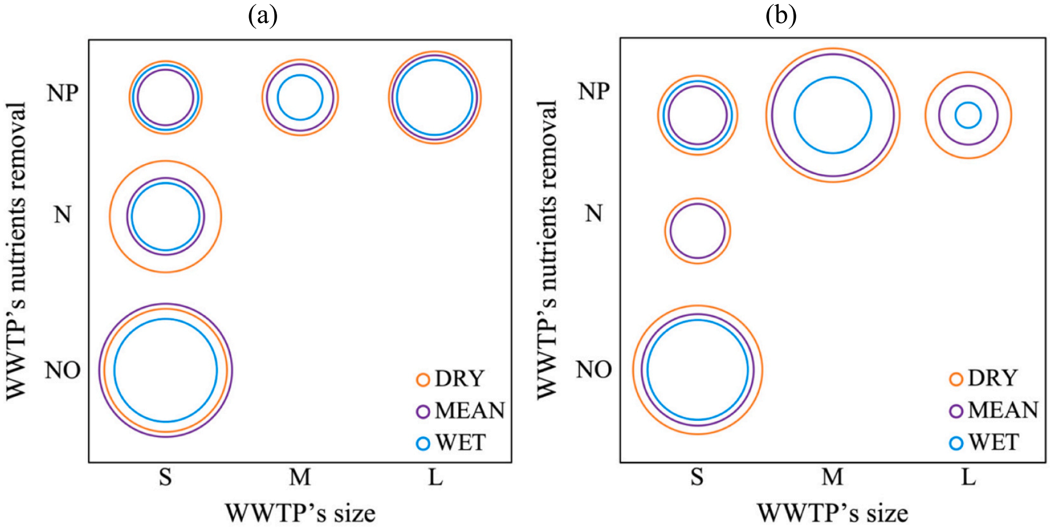


Fig. 4. Bubble charts with bubble centers located according to the classes related to WWTP size and the presence/absence of a nutrient removal process, for the three simulated rainfall patterns. Bubble diameters are proportional to the surface-specific net annual saving (€ ha^{-1} yr^{-1}) for: (a) maize, and (b) vines.

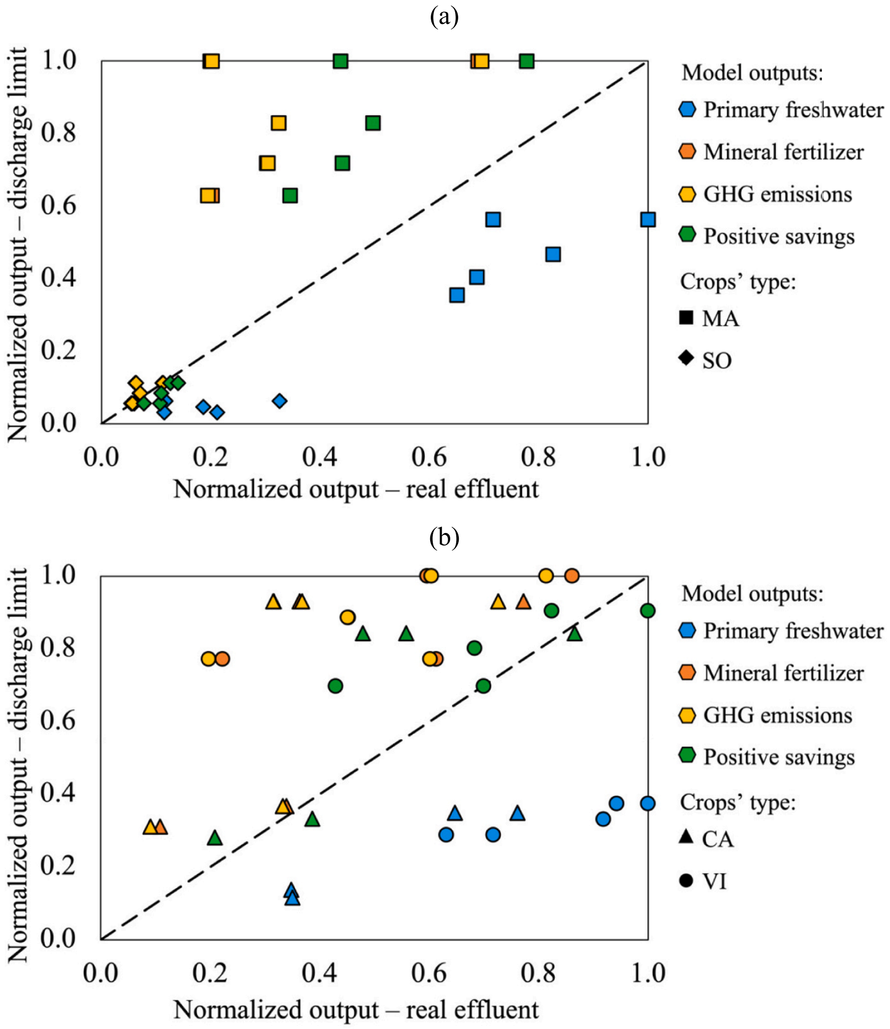


Fig. 5. Comparison of positive outputs obtained from the two simulated effluent nutrients' concentration scenarios for: (a) seed, and (b) fruits and vegetables. The axes report the normalized positive annual savings due to the model outputs indicated in the legend. Dots, differentiated per output, are located according to the values obtained in the two conditions of real effluent and discharge limit nutrients' concentration.

For all the selected crops, an increase in the effluent nutrients' concentration determines a reduction up to 85.0 % in the RWW volumes supplied to the crops, since it inherently implies that nutrients likely become the limiting factor, reducing the amount of RWW deliverable for fertigation. In the discharge limits scenario, the benefits deriving from both mineral fertilizers savings and GHG emissions reduction increase up to 80.0 % and 79.7 %, respectively, meaning that the difference in RWW nutrients' concentration is sufficiently high to counterbalance the decrease in the RWW volume supplied. However, when these two outcomes are summed up into overall savings, it becomes harder to draw general conclusions, and, once again, different crops show distinct responses to input variations. In fact, positive savings variations obtained from the increase in RWW nutrients' concentration up to the discharge limits reach their maximum with maize (up to +56.2 %), swing between positive and negative variations for carrot and vines (from −16.4 % to +43.2 %, respectively), and reach their minimum with soybean (−90.8 %).

Thus, it can be concluded that, when direct RWW reuse is implemented, an increase in effluent nutrients' concentration does not necessarily correspond to an improvement in the overall economic saving, especially considering that a common agronomic practice is to alternate different types of crops along the years, and the benefits gained in a specific year may turn into losses in the following one. These findings are in line with what obtained by Perulli et al. (2019) and Chojnacka et al. (2020), which evaluated how different types of crops are affected by different concentrations of nutrients in the irrigation water, highlighting no substantial differences in terms of crop yield.

Therefore, the restrain of the nutrient removal in WWTPs in the perspective of delivering to the crops a RWW effortlessly enriched in nutrients cannot be adopted a priori, but needs to be evaluated case by case. Even more so, higher potential risks must be considered: (i) eutrophication, due to nutrient leaching in sensitive areas following soil application of nutrient-rich effluents (Martínez-Dalmau et al., 2021), and (ii) nitrate presence in the effluents (Kiani et al., 2022), if nitrogen is not adequately removed by dedicated treatments (e.g., denitrification).

4. Conclusions

This work highlighted the potential of the developed framework to prioritize WWTPs for direct RWW reuse implementation. This prioritization is achieved through the quantification of WWTP's net annual saving by taking into account effluent characteristics (size, nutrient removal, salinity) and the nearby territory features (type of crops, rainfall pattern). This methodology provides a valuable support tool for policy-makers and water utilities since it simplifies the evaluation process for identifying the more suitable WWTPs for full-scale implementation of direct RWW reuse, by (i) classifying them through readily available characteristics, and (ii) reducing the total number of WWTPs to be further evaluated. Additionally, it aids in determining the optimal level of nutrient removal in WWTPs to maximize the economic saving of direct RWW reuse.

Primary freshwater and mineral fertilizers emerged as the major contributors to the overall economic saving, with respect to avoided GHG emissions. However, the developed model, which accounts also for the negative impacts related to an increased salinity in RWW, confirms the relevancy of this parameter to orient the decision on direct RWW reuse implementation, being responsible, for specific type of crops, to overturn the techno-economic results. Hence, to assess and prioritize the feasibility of direct RWW reuse, it is crucial to evaluate the peculiar characteristics of the crops surrounding the WWTPs, i.e., their water and nutrient requirements and their salinity threshold. Even within the same group of crops (seed and fruits and vegetables), different behaviors were pointed out related to the specific crop' subcategory (maize, soybean, carrot and vines).

WWTPs' characteristics emerged relevant as well, but with a lower influence on the net annual saving. The presence of dedicated treatments for nutrient removal resulted to be more significant than the WWTP's size, since the RWW flowrate is rarely the limiting factor, while higher RWW nutrients' concentration usually determines a higher saving. However, the potential benefits strictly depend on the specific type of crop, and the risks related to the presence of nitrate in the effluents and nutrient leaching in the environment must be carefully assessed. Actually, a proper tailoring of the reclamation treatments, the so-called "fit-for-purpose" approach, is recommended, accounting for the specific boundaries' conditions, especially the crops' type.

Since the economic feasibility of the RWW reuse implementation strongly depends on the local characteristics, the obtained results are generally valid for WWTPs with similar characteristics to the ones presented here, but they can be extended to other case studies by collecting their related site-specific data to be fed to the techno-economic model.

Further research is needed to incorporate additional variables into the model. In particular, the rainfall patterns analysis has revealed the need for considering additional environmental factors such as the freshwater availability. Moreover, including techno-economic parameters like the fee that farmers would be willing to pay for RWW as well as the costs associated with RWW transport and distribution from WWTPs to crops, would provide a more comprehensive assessment of RWW reuse feasibility, thoroughly evaluating its economic implications.

Funding

Project funded under the National Recovery and Resilience Plan (NRRP), Mission 04 Component 2 Investment 1.5 – NextGenerationEU, Call for tender n. 3277 dated 30/12/2021.

Award Number: 0001052 dated 23/06/2022.

CRediT authorship contribution statement

Luca Penserini: Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft. **Alessandro Moretti:** Data curation, Investigation, Methodology, Writing – review & editing. **Matia Mainardis:** Conceptualization, Data curation, Investigation, Validation, Writing – review & editing. **Beatrice Cantoni:** Conceptualization, Formal analysis, Methodology, Supervision, Validation, Visualization, Writing – review & editing. **Manuela Antonelli:** Conceptualization, Funding acquisition, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare no competing financial interest.

Data availability

Data will be made available on request.

Acknowledgements

The authors greatly acknowledge the water utilities Acque Bresciane S.r.l., CAFC S.p.A. and Acquedotto Poiana S.p.A. for their collaboration in data gathering.

The authors would like to thank Acque Bresciane S.r.l. for funding the Ph.D. scholarship of Luca Penserini, and CAFC S.p.A. for funding the fixed-term research position (RTD-A) of Matia Mainardis.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2023.169862.

References

Arpa FVG - Osservatorio meteorologico regionale del Friuli Venezia Giulia [WWW Document], n.d. URL https://www.meteo.fvg.it/archivio.php?ln=&p=dati (accessed 5.18.23).

Baffes, J., Koh, W.C., 2022. Fertilizer prices expected to remain higher for longer [WWW document]. URL https://blogs.worldbank.org/opendata/fertilizer-prices-expected-remain-higher-longer (accessed 5.18.23).

Bolinches, A., Blanco-Gutiérrez, I., Zubelzu, S., Esteve, P., Gómez-Ramos, A., 2022. A method for the prioritization of water reuse projects in agriculture irrigation. Agric. Water Manag. 263 https://doi.org/10.1016/j.agwat.2021.107435.

Breshears, D.D., Fontaine, J.B., Ruthrof, K.X., Field, J.P., Feng, X., Burger, J.R., Law, D.J., Kala, J., Hardy, G.E.S.J., 2021. Underappreciated plant vulnerabilities to heat waves. New Phytol. 231, 32–39. https://doi.org/10.1111/nph.17348.

Buzzacchi, C., Ferraresi, M., Galli, M., Magri, P., 2008. Stima dei fabbisogni irrigui ottimali dei consorzi di bonifica utenti del Lago di Garda.

Chojnacka, K., Witek-Krowiak, A., Moustakas, K., Skrzypczak, D., Mikula, K., Loizidou, M., 2020. A transition from conventional irrigation to fertigation with reclaimed wastewater: prospects and challenges. Renew. Sust. Energ. Rev. 130, 109959 https://doi.org/10.1016/j.rser.2020.109959.

Delli Compagni, R., Gabrielli, M., Polesel, F., Turolla, A., Trapp, S., Vezzaro, L., Antonelli, M., 2020. Risk assessment of contaminants of emerging concern in the context of wastewater reuse for irrigation: an integrated modelling approach. Chemosphere 242, 125185. https://doi.org/10.1016/j.chemosphere.2019.125185.

EU Carbon Permits - 2023 Data - 2005-2022 Historical - 2024 Forecast - Price - Quote [WWW Document], n.d. URL https://tradingeconomics.com/commodity/carbon (accessed 5.22.23).

EU Commission, 2020. Regulation (EU) 2020/741 of the European Parliament and of the Council of 25 May 2020 on minimum requirements for water reuse. Off. J. Eur. Union 2019, 32–55.

FAO, 1994. Water quality for agriculture, 2nd ed, LymphoSign J.

FAO website. Prices | FAO | Food and Agriculture Organization of the United Nations. URL https://www.fao.org/prices/en/ (accessed 5.26.23).

Fertilgest website. Colture - Fertilgest. URL https://fertilgest.imagelinenetwork.com/it/colture/?ref=home-page (accessed 5.22.23).

Gao, Y., Shao, G., Wu, S., Xiaojun, W., Lu, J., Cui, J., 2021. Changes in soil salinity under treated wastewater irrigation: a meta-analysis. Agric. Water Manag. 255, 106986 https://doi.org/10.1016/j.agwat.2021.106986.

Giannoccaro, G., Arborea, S., de Gennaro, B.C., Iacobellis, V., Piccinni, A.F., 2019. Assessing reclaimed urban wastewater for reuse in agriculture: technical and economic concerns for Mediterranean regions. Water (Switzerland) 11. https://doi.org/10.3390/w11071511.

Khan, M.M., Siddiqi, S.A., Farooque, A.A., Iqbal, Q., Shahid, S.A., Akram, M.T., Rahman, S., Al-Busaidi, W., Khan, I., 2022. Towards sustainable application of wastewater in agriculture: a review on reusability and risk assessment. Agronomy 12. https://doi.org/10.3390/agronomy12061397.

Kiani, A., Sharafi, K., Omer, A.K., Matin, B.K., Davoodi, R., Mansouri, B., Sharafi, H., Soleimani, H., Massahi, T., Ahmadi, E., 2022. Accumulation and human health risk assessment of nitrate in vegetables irrigated with different irrigation water sources-transfer evaluation of nitrate from soil to vegetables. Environ. Res. 205, 112527 https://doi.org/10.1016/j.envres.2021.112527.

Mainardis, M., Cecconet, D., Moretti, A., Callegari, A., Goi, D., Freguia, S., Capodaglio, A. G., 2022. Wastewater fertigation in agriculture: issues and opportunities for improved water management and circular economy. Environ. Pollut. 296, 118755 https://doi.org/10.1016/j.envpol.2021.118755.

Martínez-Dalmau, J., Berbel, J., Ordóñez-Fernández, R., 2021. Nitrogen fertilization. A review of the risks associated with the inefficiency of its use and policy responses. Sustain 13, 1–15. https://doi.org/10.3390/su13105625.

Moreira da Silva, M., Resende, F.C., Freitas, B., Aníbal, J., Martins, A., Duarte, A., 2022. Urban wastewater reuse for Citrus irrigation in Algarve, Portugal—environmental benefits and carbon fluxes. Sustain 14. https://doi.org/10.3390/su141710715.

Ofori, S., Puškáčová, A., Růžičková, I., Wanner, J., 2021. Treated wastewater reuse for irrigation: pros and cons. Sci. Total Environ. 760 https://doi.org/10.1016/j.scitotenv.2020.144026.

Perulli, G.D., Bresilla, K., Manfrini, L., Boini, A., Sorrenti, G., Grappadelli, L.C., Morandi, B., 2019. Beneficial effect of secondary treated wastewater irrigation on nectarine tree physiology. Agric. Water Manag. 221, 120–130. https://doi.org/10.1016/j.agwat.2019.03.007.

Pistocchi, A., Aloe, A., Dorati, C., Alcalde Sanz, L., Bouraoui, F., Gawlik, B., Grizzetti, B., Pastori, M., Vigiak, O., 2018. The potential of water reuse for agricultural irrigation in the EU a hydro-economic analysis. https://doi.org/10.2760/263713.

Quinteiro, P., Rafael, S., Vicente, B., Marta-Almeida, M., Rocha, A., Arroja, L., Dias, A.C., 2019. Mapping green water scarcity under climate change: a case study of Portugal. Sci. Total Environ. 696, 134024 https://doi.org/10.1016/j.scitotenv.2019.134024.

Ricart, S., Rico, A.M., 2019. Assessing technical and social driving factors of water reuse in agriculture: a review on risks, regulation and the yuck factor. Agric. Water Manag. 217, 426–439. https://doi.org/10.1016/j.agwat.2019.03.017.

Richiesta dati misurati - Meteorologia | ARPA Lombardia [WWW Document], n.d. URL https://www.arpalombardia.it/Pages/Meteorologia/Richiesta-dati-misurati.aspx (accessed 5.18.23).

Rossi, G., Mainardis, M., Aneggi, E., Weavers, L.K., Goi, D., 2021. Combined ultrasound-ozone treatment for reutilization of primary effluent—a preliminary study. Environ. Sci. Pollut. Res. 28, 700–710. https://doi.org/10.1007/s11356-020-10467-y.

Schober, P., Schwarte, L.A., 2018. Correlation coefficients: appropriate use and interpretation. Anesth. Analg. 126, 1763–1768. https://doi.org/10.1213/ANE.0000000000002864.

Slafer, G.A., Savin, R., 2018. Can N management affect the magnitude of yield loss due to heat waves in wheat and maize? Curr. Opin. Plant Biol. 45, 276–283. https://doi.org/10.1016/j.pbi.2018.07.009.

Toreti, A., Bavera, D., Acosta Navarro, J., Cammalleri, C., de Jager, A., Di Ciollo, C., Hrast Essenfelder, A., Maetens, W., Masante, D., Magni, D., Mazzeschi, M., Spinoni, J., 2022. Drought in Europe August 2022. Publ, Off. Eur. Union. https://doi.org/10.2760/264241.

Trajkovic, S., Kolakovic, S., 2009. Wind-adjusted Turc equation for estimating reference evapotranspiration at humid European locations. Hydrol. Res. 40, 45–52. https://doi.org/10.2166/nh.2009.002.

Vivaldi, G.A., Zaccaria, D., Camposeo, S., Pasanisi, F., Salcedo, F.P., Portoghese, I., 2022. Appraising water and nutrient recovery for perennial crops irrigated with reclaimed water in Mediterranean areas through an index-based approach. Sci. Total Environ. 820, 152890 https://doi.org/10.1016/j.scitotenv.2021.152890.